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Evaluation of DWDM-FSO Environment Based on OFDM Modulation Technique

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ABSTRACT

Dense wavelength division multiplexing (DWDM) has emerged as a promising technique for meeting rising bandwidth demands in optical networks. It has been used to boost the capacity of long-distance optical transport systems like free space optics (FSO) and optical fibre. FSO communication is an optical communication technology that sends optical data wirelessly from one location to another. Q-Factor and the BER analyser are used to assess the signal strength of the received signal. DWDM over FSO communication system is very effective in providing high data rate transmission with a very low bit error rate (BER). The maximum reach of the proposed system is 100 km without any compensation scheme. By implementing the OFDM Modulation Technique, four channels of DWDM over a FSO communication system were successfully demonstrated and has been analysed for higher data rate and the better quality of BER. The 15 Gb/s data rate with channel spacing at 0.8 nm and input power of 15 dBm, covered the distance up to 100 km. To show the good performance of the proposed system, its BER, and Q factor are shown. A sharp increase in BER occurs if data rate and distance increase up to 21 Gb/s and 100 km. The simulations are carried out using OptiSystem version 17.0 commercial optical system simulator.

Keywords:
DWDM; OWC; OFDM; FSO

1. Introduction

Fibre optic cables have become the industry standard for telecommunications infrastructure, serving as the backbone of carriers' interoffice networks. DWDM allows massive amounts of data to traverse a single network link by forming multiple virtual fibres, significantly multiplying the physical medium's capacity. DWDM is an optical fibre multiplexing technique that is used to increase the bandwidth of existing fibre networks. It combines data signals from multiple sources while keeping the data streams separate over a single pair of optical fibre DWDM can accommodate up to 80

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different wavelengths, and each signal is carried by a different light wavelength. Each signal is carried by a different wavelength of light, and the dense in DWDM refers to its ability to accommodate up to 80 different wavelengths. Each wavelength is about 0.8 nm wide and shared by a single optical fibre [1]. Furthermore, many researchers use multiplexing schemes such as DWDM to increase the capacity of optical communication systems wavelengths.

FSO communication systems have emerged as a technological revolution in wireless communication, also known as optical wireless communications, and have recently received a lot of attention as a promising solution for high-rate last-mile terrestrial communications. FSO transmits data over the air in a line-of-sight manner using infrared laser beams. The laser beams are concentrated into a narrow beam, which helps to reduce the effects of atmospheric turbulence and other environmental factors that can interfere with signal transmission. The ability to quickly establish a communication link without the use of physical cables is one of FSO's main advantages, as is its high bandwidth potential. Its transmission range, however, is limited by atmospheric conditions such as fog and rain, which can interfere with the laser beams [2,3]. The DWDM over FSO communication system provides extremely high-rate transmission with a very low BER. With FSO and DWDM, the number of channels can be increased, improving technical capacity and utility for long-distance data transmission [4,5].

This paper analysed the performance of DWDM-FSO environment based on OFDM modulation technique. It aims to acquire a better data rate and the best quality of BER while using OFDM technique with the potential high data rate capacity, low cost, and particularly wide bandwidth on unregulated spectrum. In addition, implementing advanced OFDM techniques such as adaptive bit loading and dynamic subcarrier allocation can maximize spectral efficiency, enabling higher data rates over the FSO link compared to traditional modulation schemes. In this research, the FSO system is used to provide a low-cost protocol transparent link with high data rates. Multicarrier modulation is used in the OFDM technique system. An OFDM signal is made up of a series of closely spaced modulated carriers. To successfully demodulate data, a receiver must be able to receive the entire signal.

1.1 Theoretical Review

WDM has been the preferred technology for transporting large volumes of data between sites for an extended period. It increases bandwidth by allowing different data streams to be sent simultaneously over a single optical Fibre network. In this way WDM maximizes the usefulness of Fibre and helps optimize network investments. Therefore, it serves as a Fibre optic transmission technique that enables the use of multiple light wavelengths (or colours) to send data over the same medium. Two or more colours of light can travel on one Fibre, and several signals can be transmitted in an optical waveguide at differing wavelengths or frequencies on the optical spectrum [6].

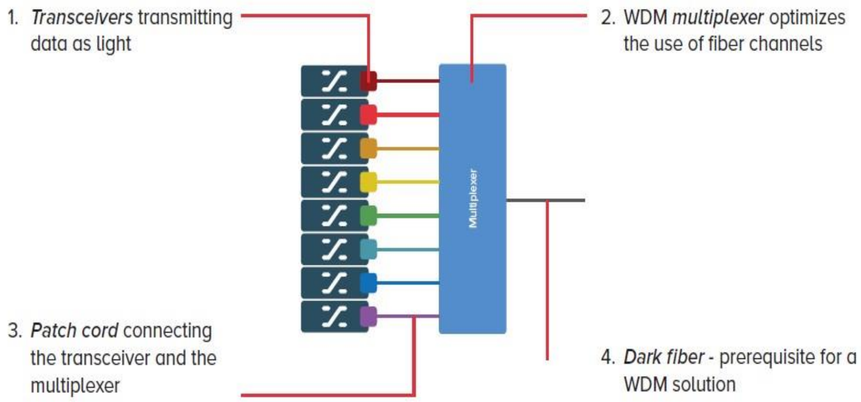


Fig. 1. Simplest form WDM system consists of four elements [6]

WDM is an optical transport technology that divides existing dark fibre into multiple channels of traffic to simultaneously transport several streams of data, like increasing the number of lanes on a highway to make the flow of traffic more efficient. WDM networks use multiple colours of light, or wavelengths, over the same common path (fibre). Optical transmitters tuned to specific wavelengths send light into a passive combiner called a mux [7].

Meanwhile, DWDM is a subset of WDM technology which is an optical fibre multiplexing technology that is used to increase the bandwidth of existing fibre networks. It combines data signals from different sources over a single pair of optical fibre, while maintaining complete separation of the data streams. DWDM has tighter wavelength spacing that helps fit more channels onto a single fibre. It is best used in systems with more than eight active wavelengths per fibre. Because DWDM finely dices the spectrum, it can easily fit over 40 channels into the C-band frequency range. Dense wavelength-division multiplexing in optical fibre systems deployed today achieves a throughput of 100 Gb/s. When DWDM is used with network management systems and add-drop multiplexers, carriers can adopt optically based transmission networks. This approach helps meet growing bandwidth demand at a significantly lower cost than installing new fibre [8,9].

On the other hand, Orthogonal Frequency Division Multiplexing (OFDM) is a type of signal waveform or modulation that offers significant benefits for data links. As a result, OFDM is used in many of the most recent wide bandwidth and high data rate wireless systems, such as Wi- Fi, cellular telecommunications, and many others. Because OFDM employs a large number of carriers, each carrying low bit rate data, it is highly resistant to selective fading, interference, and multipath effects, while also providing a high level of spectral efficiency. Early systems that used OFDM discovered that the processing required for the signal format was relatively high, but with technological advances, OFDM now presents few issues in terms of the processing required. To see how OFDM works, it is necessary to look at the receiver. This acts as a bank of demodulators, translating each carrier down to DC. The resulting signal is integrated over the symbol period to regenerate the data from that carrier. The same demodulator also demodulates the other carriers. As the carrier spacing equal to the reciprocal of the symbol period means that they will have a whole number of cycles in the symbol period and their contribution will sum to zero in other words there is no interference contribution [10-12].

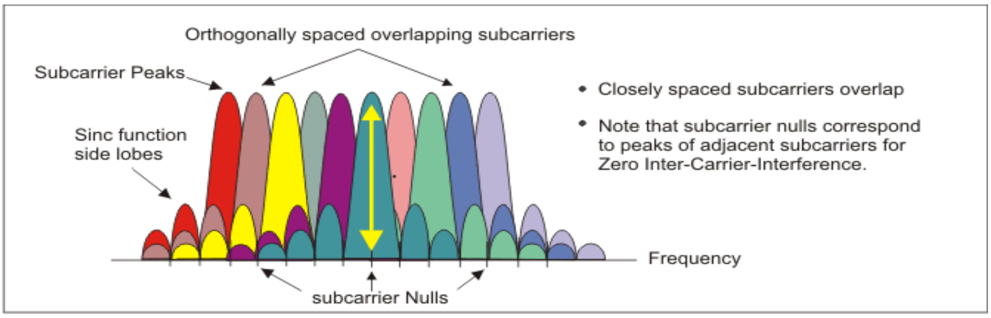


Fig. 2. Basic concept of Orthogonal Frequency Spectrum [10]

1.2 Previous Work on DWDM-FSO

DWDM was used by various researchers over various transmission mediums such as (SMF, OWC, and FSO) based on different distances and capacities [13,14]. In the year 2016, the author adequately showed a 40 Gb/s DWDM over 4000 m FSO connection solution. The performance findings investigated the DWDM over FSO and designed utilizing RZ modulation with numerous parameters, FSO transmitter and receiver diameter, signal power, beam divergence, and varying distances and attenuation [15].

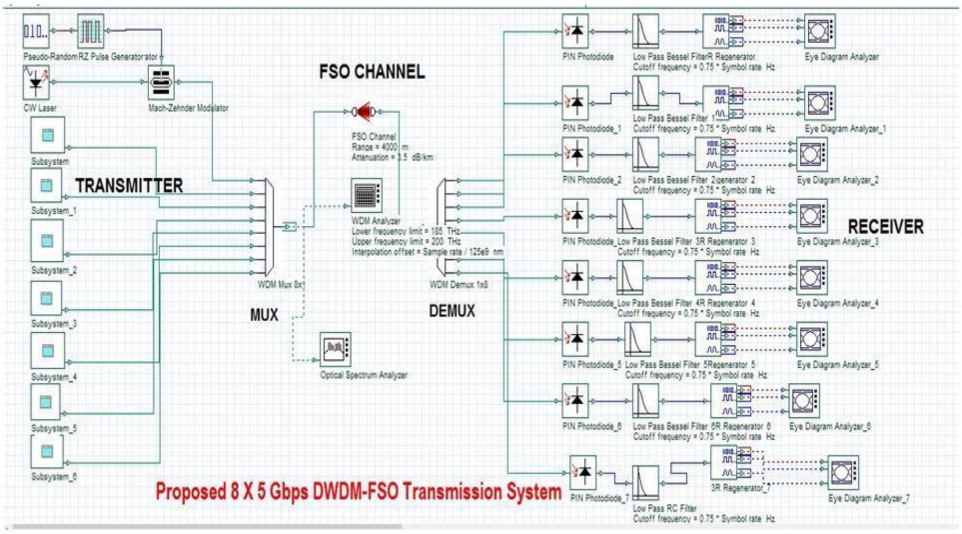


Fig. 3. Proposed 8 X 5Gb/s DWDM-FSO Transmission System by using OptiSystem software [15]

On top of that in 2021, a researcher published a different technique, about DWDM over FSO, but using a different technique that is to the hybrid on-off keying (OOK) modulation, M-ary digital pulse position modulation (M-ary DPPM), and M-pulse amplitude and position modulation are used to improve the performance efficiency of the FSO communication link (M-PAPM). This study examines and improves the BER performance of the moment generating function in an atmospheric turbulence channel [14].

Numerous research articles emphasize various features of FSO systems together with DWDM architecture. The research shown in [16] investigated the performance of 3-D orthogonal modulation technique that leverages various signal characteristics of an optical laser beam such as intensity, phase, and polarization state to concurrently transmit three distinct 40 Gb/s data streams over a solitary optical carrier signal. This approach achieved a cumulative transmission rate of 120 Gb/s per wavelength channel. An 8x10 Gb/s with return to zero (RZ) wavelength division multiplexed (WDM)-

based FSO system using differential phase-shift keyed (DPSK) signals has been proposed for a link under various weather conditions [17], whereas the four advanced modulation formats have been compared to achieve a 10 Gb/s transmission link for a maximum link distance of 7 km [18]. The performance of CO-OFDM and spatial diversity-based DWDM-FSO system has been analysed to minimize the impacts of the atmospheric disturbances and enhance the performance to achieve a 10 Tb/s data [13]. The investigation of DWDM over FSO was proposed with different atmospheric attenuations. This article investigated eleven-channel DWDM over FSO using an electrical linear equalizer to improve receiver performance. The channel7 spacing is at 1.2 nm based on the traditional International Telecommunication Union (ITU) grid. The system transmits 110 Gb/s for FSO distances 9500 m, 3000 m, and 2500 m in superbly clear air, haze, and heavy haze atmospheric attenuations, respectively [19].

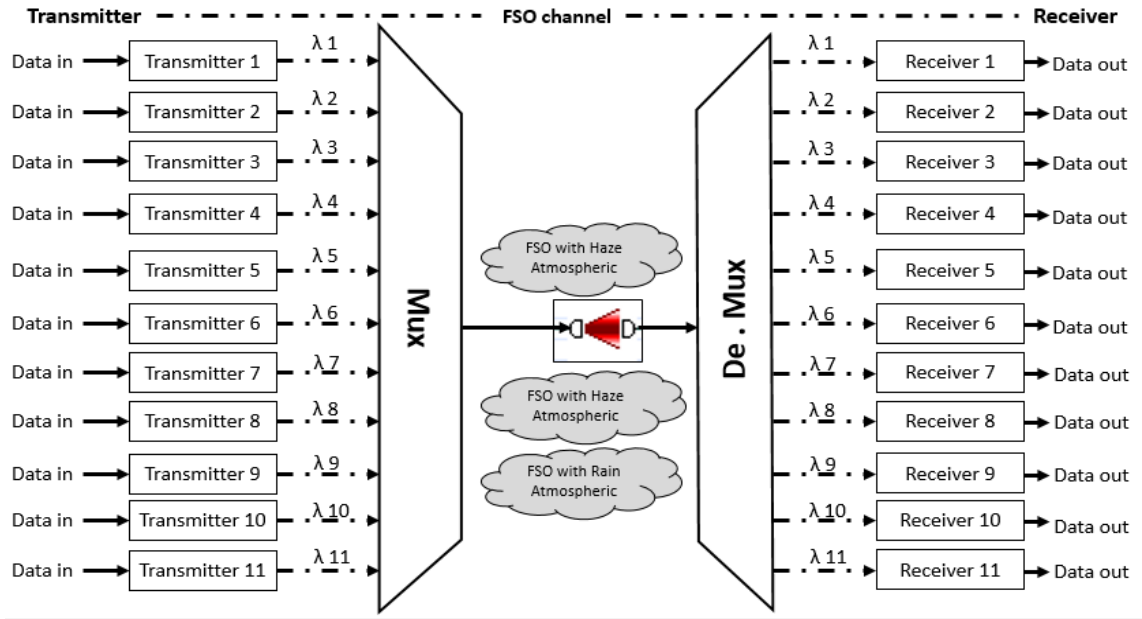


Fig. 4. Optical DWDM over FSO under the effect of clear air atmospheric attenuation, haze atmospheric attenuation, and atmospheric rain attenuation [13]

2. Methodology
2.1 System Design

The block diagram of the proposed system is shown in Figure 5. The transmitter section is made up of a pseudo random bit sequence generator, a QAM Sequencer, an OFDM Modulator, a Quadrature Modulator, a Continuous Wave Laser, and a Mach Zehnder Modulator. As dense wavelength division multiplexing is used, four channels 1550 nm to 1552.4 nm are considered, with a channel spacing of 0.8 nm (100 GHz). The multiplexing technique is used to combine numerous signals into a single transmission medium, allowing multiple transmitters or sources to share the same channel efficiently. However, the specific multiplexing technique utilized is determined by the environment and the nature of the signals being conveyed. The data rate and power consumption are 15 Gb/s and 15 dBm, respectively. This modulated light from transmitters travels through free space, or the atmosphere. This condition is first investigated in clear weather, with an attenuation value of 0.2 dB/km. A free space optical channel is a subsystem that consists of a transmitter telescope and a receiver telescope that serve as antennas. These signals are demultiplexed and routed to the appropriate receivers, with each receiver section consisting of a PIN Photodiode, QAM

Sequence Decoder, OFDM Demodulator, Quadrature Demodulator, 3R regenerator, and a BER analyser/Eye diagram from which the quality factor and BER are estimated.

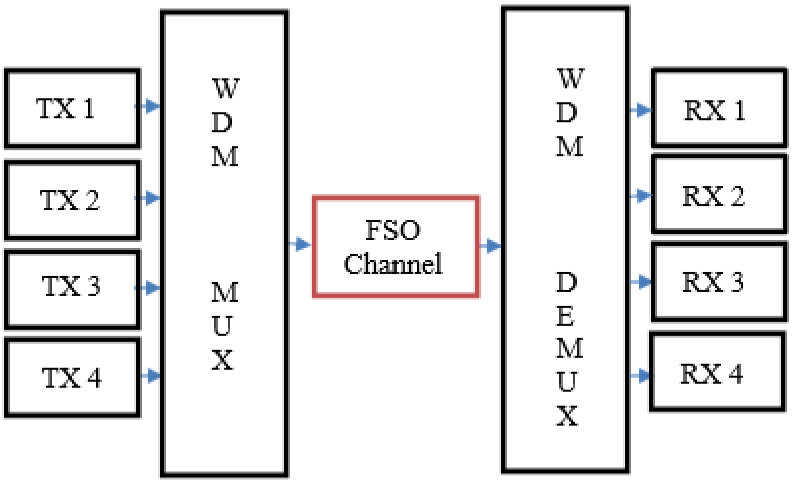
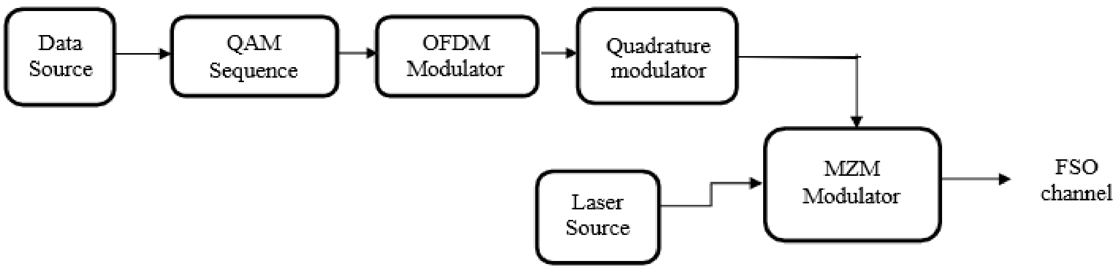


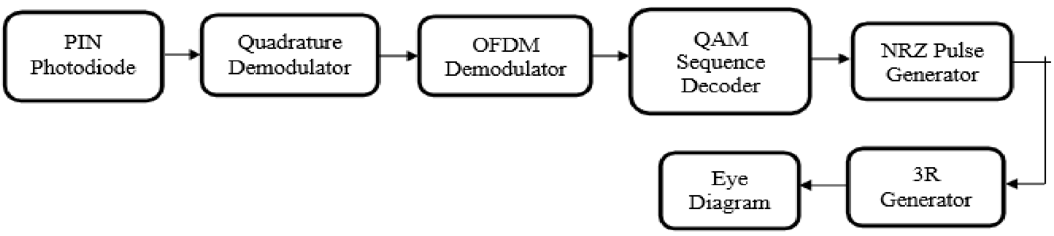
Fig. 5. Block diagram of DWDM over FSO

2.2 OFDM Modulation Technique System

Figure 6(a) depicts an OFDM transmitter's block diagram. The optical transmitter converts an electric signal to an optical signal, which is then fed into a free space channel. The optical transmitter is made up of an optical source, such as a light-emitting diode (LED), and an optical modulator, which can be either direct or external, such as a Mach-Zehnder Modulator (MZM). The OFDM modulator performs both multiplexing and modulation digitally during transmission by utilizing an inverse fast Fourier transform (IFFT). A CW laser and MZM are used to turn up-conversion (RF to optical), and the I and Q elements are modulated separately by a quadrature modulator. At the transmission, the OFDM modulator, both multiplexing and modulation are digitally achieved utilizing an inverse fast Fourier transform (IFFT).



(a)



(b)

Fig. 6. (a) Block diagram OFDM Transmitter (TX); (b) Block diagram Receiver section (RX)

The peak power of laser is set to 15 dB for each channel. Figure 6(b) represents optical spectrum measured at output of transmitter. At the receiver side, each channel is demodulated by PIN photodiodes followed by Quadrature Demodulator with cut-off frequency of 10 GHz. The end RF signal of the receiver is demodulated using the inverse logic used for demodulating and recovering the signal. It is a PIN photodiode with a typical responsivity of 1 A/W at 1550 nm and a dark current of 10 nA that is used. The detector's electrical output signal is duplicated by a quadrature demodulator before being multiplied by sine and cosine carriers. The performance of the proposed high speed FSO system is measured in terms of BER and quality factor (Q).

2.3 Parameter for System Design

Table 1 shows parameters used for the system design.

Table 1
Parameter values of system design

Parameter	Description
Number of channels	4
Channel Spacing	0.8 nm
Range	50 km
Attenuation	0.2 dB/km
Data Rate/Bit Rate	15 Gb/s
Signal Power	10nA

2.4 Simulation Design

Figure 7 represents a four-channel DWDM-FSO simulation design using the OFDM technique. This system is used to analyse the performance of OFDM in relation to the environment, such as whether it can be used for the highest data rate and longest distance, as well as the attenuation that is appropriate for the system to work. The related previous work using OptiSystem software can also be found in [20].

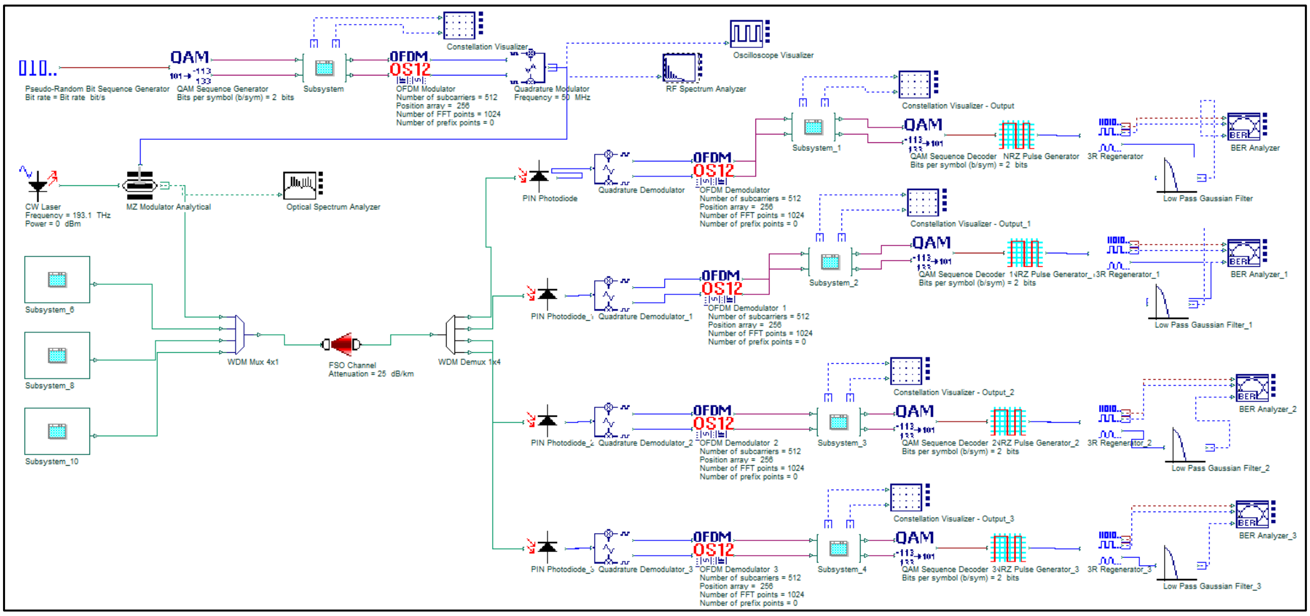


Fig. 7. DWDM-FSO based on OFDM technique simulation

Figure 8 depicts the 2.5GHz random binary bits carried by the 2 GHz carrier frequency being OFDM modulated using an OFDM transmitter block, followed by signal modulation using a MZ Modulated. A CW laser source generates an optical signal that is applied to the input port, yielding I and Q carrier components that are used to power the MZMs.

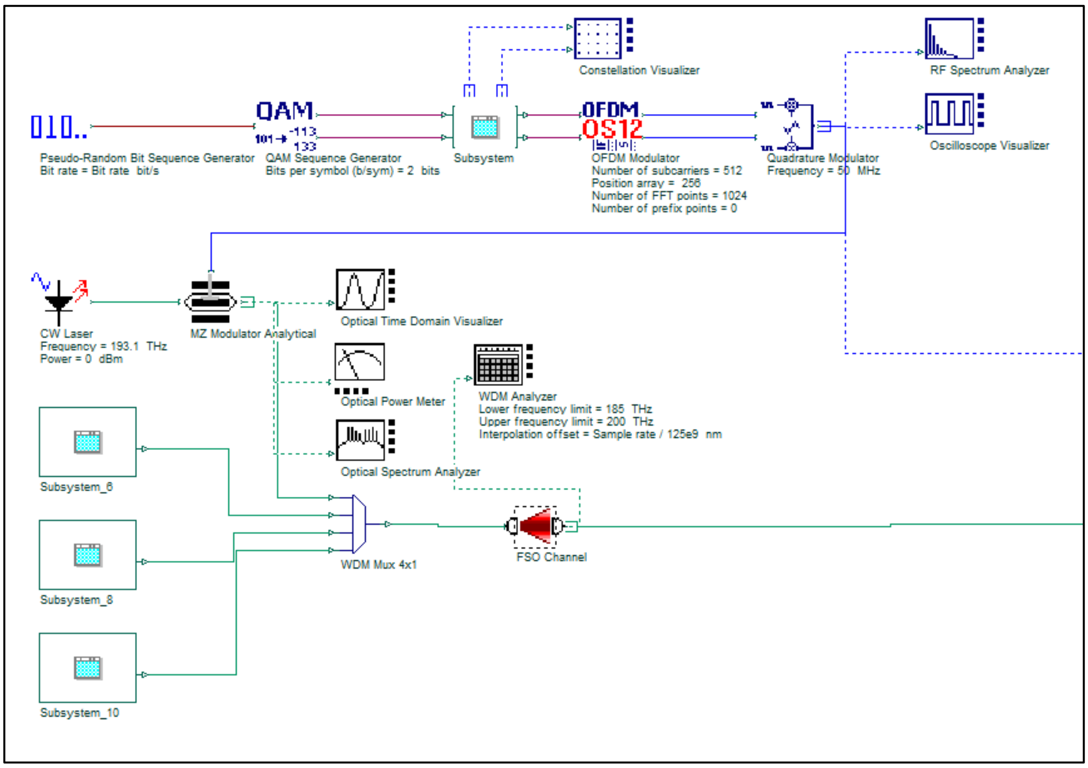


Fig. 8. OFDM transmitter system

The controlling of each MZM can be done with positive and negative signals of the components of I or Q baseband OFDM modulating signal at MZM inputs, while Figure 9 depicts the part of receiver for DWDM-FSO using OFDM technique, that transforms the optical data into electrical form at the receiving end. The initial step is to detect data in optical form and convert it into an electrical signal using a high sensitivity receiver PIN Photodiode. An OFDM demodulator is then supplied with the I and Q signals from the quadrature demodulator. The signal is divided into individual subcarriers by the OFDM demodulator, which then extracts the transmitted data from each subcarrier. A QAM sequence decoder continues to handle the subcarriers after the OFDM demodulation is complete. The data encoded in the subcarriers is decoded by the QAM sequence decoder, which also recovers the original QAM-modulated sequence. After the QAM sequence has been decoded, it is changed to the Non-Return-to-Zero (NRZ) format. Data is represented as binary 1s and 0s in NRZ encoding without any further signal encoding. A 3R generator receives the signal that has been NRZ-encoded. By increasing the signal's amplitude, modifying its waveform, and retiming it to the appropriate timing references, the 3R generator improves the signal's quality. We are aware that noise in the form of interference between symbols may arise because data is transmitted in the digital domains 0 and 1. Therefore, we employed a device known as the BER Tester to measure the inaccuracy. Those simulation parameters are configured as in Table 1.

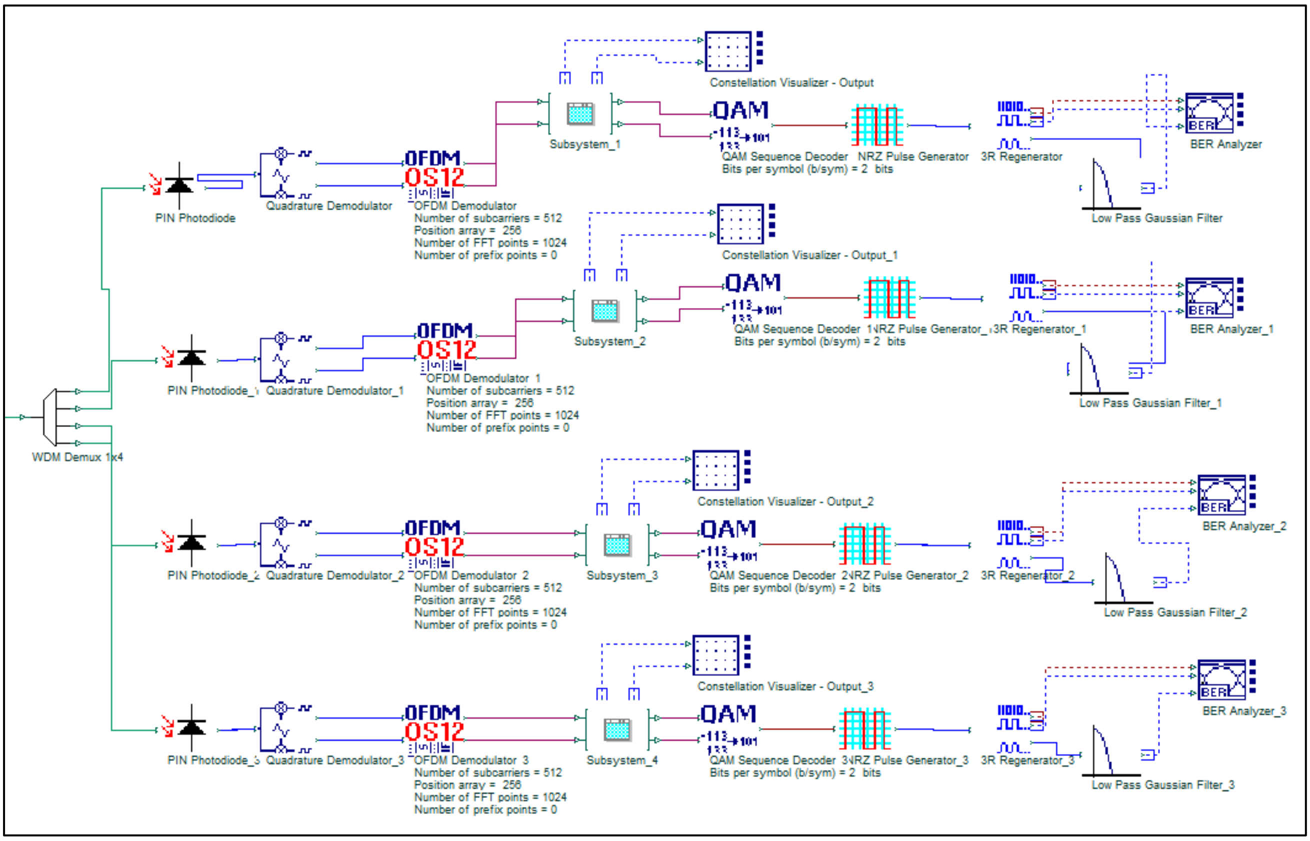


Fig. 9. DWDM-FSO using OFDM technique receiver system

3. Results

3.1 DWDM-OFDM System

Figure 10 depicts the output of the Quadrature Modulator of the QAM-OFDM system using the 256-QAM modulation scheme over a transmission distance of 50-100 km. Reading of the RF spectrum obtained from a 15 dBm transmitter. Before this signal can be transmitted over a 50 km optical fibre, the coherent receiver must be read. As shown in Figure 11, power is reduced to -15.5 dBm. The OFDM of the RF signal generated by a quadrature modulator that modulates a technique that uses two signals to amplitude-modulate two carriers in quadrature that is shown in Figure 10 the RF baseband spectrum frequency with corresponding bandwidth. Alternatively, an OFDM signal with four subcarriers modulated with a 4-QAM scheme and up converted to a carrier frequency of 15 GHz with a quadrature modulator before optically modulating can yield the desired result.

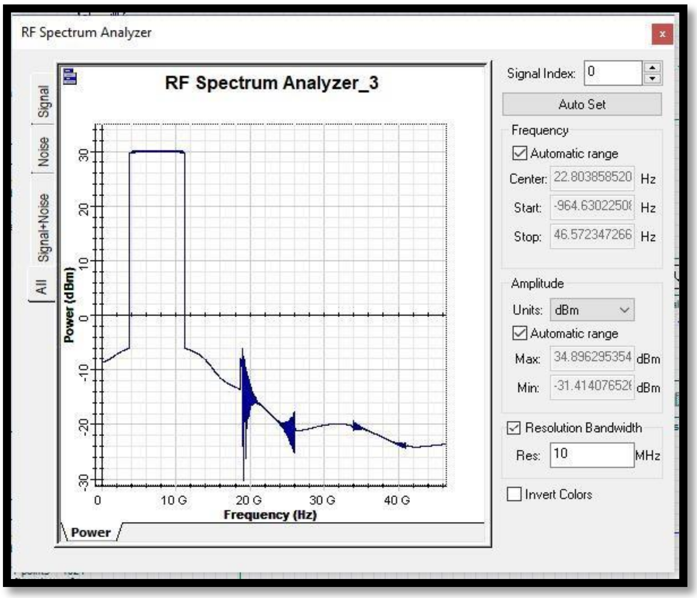
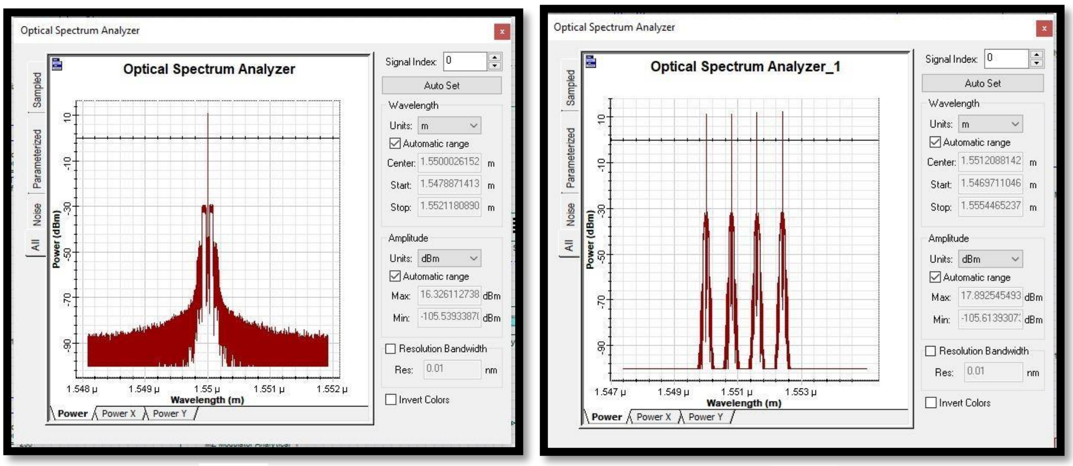


Fig. 10. Quadrature Modulator RF Spectrum at Transmitter

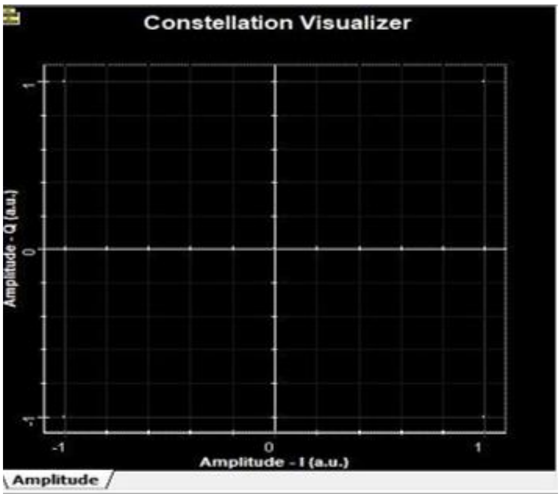
Figure 11(a) depicts an optical spectrum signal implemented to an electro-optic modulator (MZM) on which it is modulated with a higher carrier frequency and its centre frequency is started to shift to 7.5 GHz with both sides of subcarrier bands and the CW laser of modulation formats centred at 1550 nm. The output is an optical carrier with a double side-band, symmetric and centred around 1550 nm, with upper sideband at 1550.55 nm. Figure 11(b) shows the transmission wavelength of four FSO channel spectrums. Those four DWDM channels with 50 GHz channel space are available, ranging from 1548 nm to 1554 nm and are selected for observation of DWDM-FSO communication system.

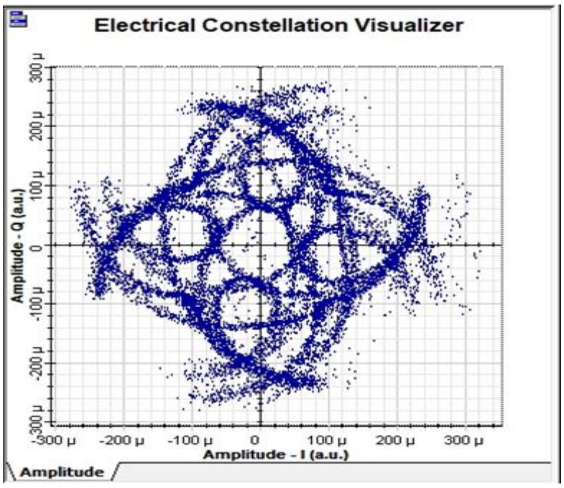


(a) (b)

Fig. 11. (a) Optical Spectrum at OFDM Transmitter (b) Signal after WDM Multiplexing

Figure 12(a) below shown, the constellation diagram at the transmitter. This is a constellation diagram for 4-QAM modulator. Figure 12(b) shows the constellation diagram after 100 km and data rate 15 Gb/s. To represent the various points on the constellation diagram, the amplitude and phase of the carrier signal are varied. A higher data rate can be achieved by using a larger constellation with more points, but this also increases the susceptibility to noise and other impairments, high-speed communication systems such as cable modems, digital subscriber lines (DSL), and wireless LANs were used for 256-QAM. Higher data rate than lower order modulation schemes like QPSK (Quadrature Phase Shift Keying) and 16-QAM but requires more bandwidth and a higher signal-to-noise ratio to ensure reliable signal transmission.





(a) (b)

Fig. 12. (a) Constellation diagram at OFDM transmitter (b) Constellation diagram at receiver after 100 km

3.2 Data Rate and Distance Comparison at BER

BER is one of the performance indicators to analyse the overall system performance [21]. Table 2 below shows a comparison of data rates at 15, 18, and 21 Gb/s for distance at 50 km and Bit Error Rate (BER) at first channel to determine which data rate is best for this system and environment. As mentioned in the previous chapter, the higher the data rate, the worst the system's performance but still acceptable to be used.

Table 2
Comparison between Data Rate and Distance at BER

Data Rate	Distance/FSO Range	BER Channel 1
15 Gb/s	50 km	$4.8903e^{-163}$
18 Gb/s	50 km	$5.03901e^{-026}$
21 Gb/s	50 km	$5.57039e^{-009}$

3.3 Analysis Result

The BER and Q-factor for channels 1 at three different distances of 50 km, 75 km, and 100 km at a data rate of 21 Gb/s are shown in Table 3. According to research, the longer the distance, the better the quality of the received signal, and the higher the data rate, the performance has been degraded.

Table 3
BER and Q-factor values for channels 1 at distances of 50 km, 75 km, and 100 km at data rate of 21 Gb/s

Distance/FSO range	BER	Q-Factor
50 km	$5.57039e^{-009}$	5.71235
75 km	$3.00561e^{-009}$	5.81644
100 km	$1.29176e^{-009}$	5.95605

As we can see in Figure 13 and Figure 14 below show the different value for Bit Error Rate (BER) between two different data rates and two different distances. It has been demonstrated that BER at 50 km for 15Gb/s is the best highest data rate that we can used in OFDM technique, and that the system can be used to provide a better signal for users.

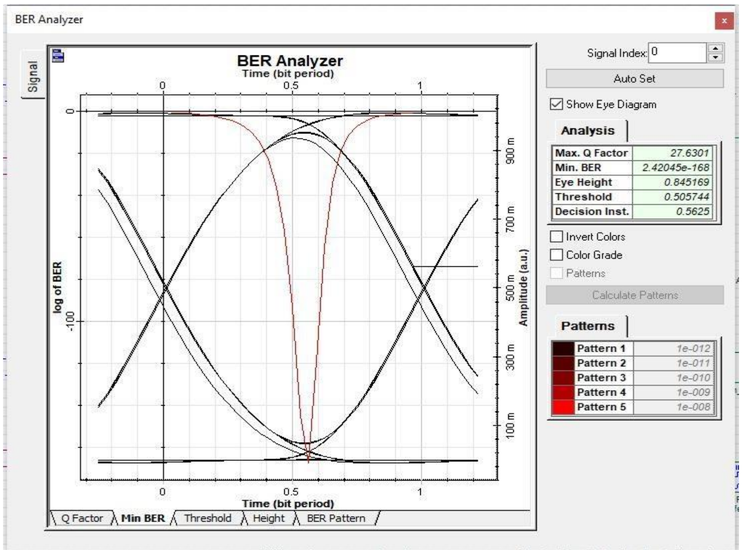


Fig. 13. BER analyzer for 50km at 15 Gb/s

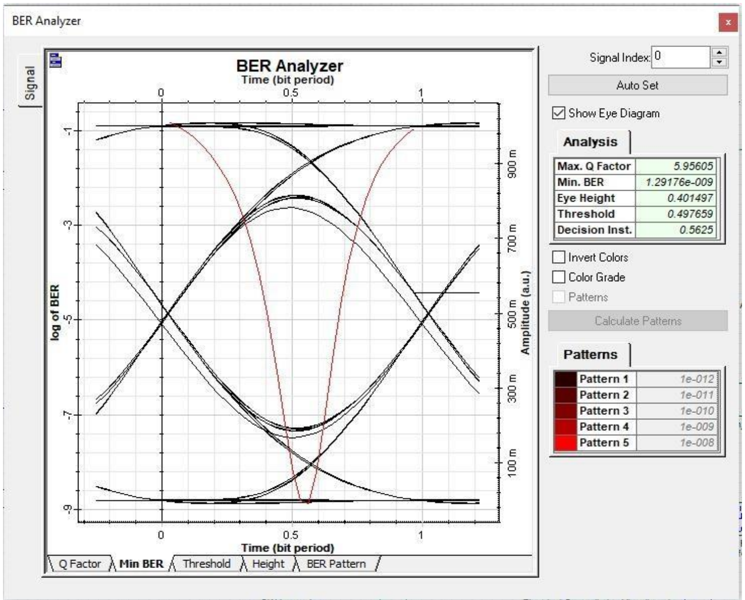


Fig. 14. BER analyzer for 100km at 21 Gb/s

Figure 15 shows the BER versus distance at 50 km for OFDM modulation format and Table 4 represents the BER for different channel 1 and 2 at 50 km, 75 km, and 100 km. For channels 1 and 2 the BER values are $3.05922e^{-165}$ and $1.31384e^{-168}$ for OFDM modulation format. So, it has been observed that if the FSO channel range increases BER also increases.

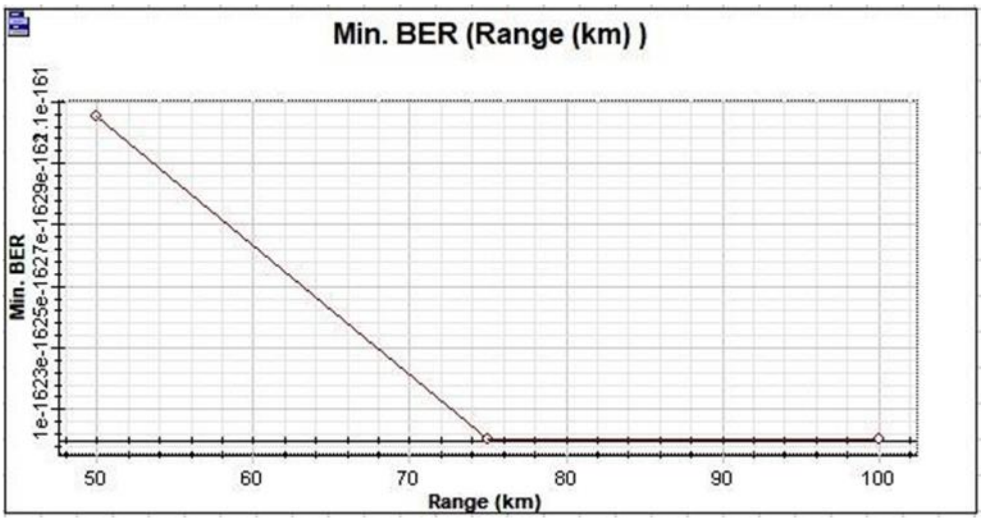


Fig. 15. BER versus distance value for 50 km, 75 km, and 100 km at Channel 2

Table 4
BER value for channels 1 and 2 at 50 km, 75 km, and 100 km distances and data rate of 15 Gb/s Receiver

Distance/FSO range	BER Channel 1	BER Channel 2
50 km	$2.42045e^{-168}$	$5.17138e^{-166}$
75 km	$3.14282e^{-180}$	$1.81156e^{-162}$
100 km	$1.81193e^{-173}$	$3.4237e^{-171}$

Figure 16 shows Q-factor versus distance at 50 km for MRZ modulation format. For channel 1 and 2 also the Q-values are 27.6301 and 27.4355 at 50 km for OFDM modulation format. It has been observed that distance also influences the quality of received signal. If distance increases the quality of received signal decreases.

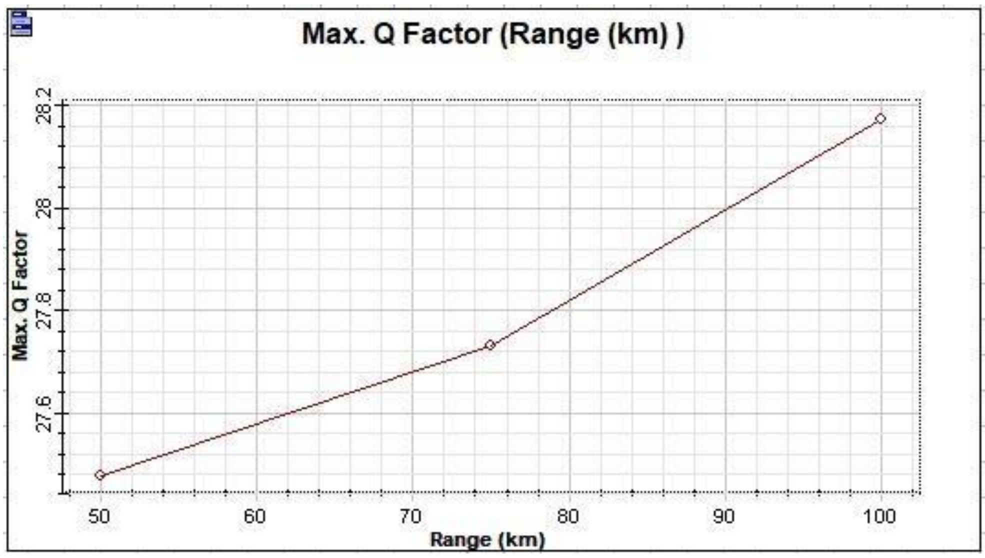


Fig. 16. Q-factor versus distance value for 50 km, 75 km, and 100 km at Channel 2

Figure 17 shows distance versus signal power at 50 km, 75 km, and 100 km. For Channels 2 the signal power is found to be 26.15, 27.50, and 27.25 for 10 nA signal power. Signal power is an important consideration because it influences transmission quality and reliability. A stronger signal can improve the signal-to-noise ratio (SNR), which is the ratio of signal power to noise power in a transmission. A higher SNR indicates that the signal can be distinguished from the background noise, resulting in improved reception and fewer errors. The power of a signal can be increased by using a more powerful transmitter or by amplifying the signal with a signal booster or amplifier. However, increasing signal power can cause interference with other signals, so it's critical to strike a balance between signal strength and interference avoidance. So, it has been observed that signal power also affects quality of received signal.

Fig. 17. Signal power versus distance/range

Based on literature review on the most related previous work, performance comparison has been summarized in Table 5.

Table 5
Performance comparison with previous work

Research work	Method	Remarks
[13]	Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) with dual polarization with FSO system using DWDM based on spatial diversity.	Use of spatial diversity and DWDM OFDM with dual polarization in the system of FSO increased the efficiency of systems under various disturbances with 10Gb/s data rate.
[16]	WDM-FSO based 3-D orthogonal modulation scheme.	Achieved 3.84 Tb/s transmission over FSO with maximum link range of 40 km for 32 channels.
[17]	RZ-DPSK based WDM-FSO system with FEC methos.	An 8x10 Gb/s under link support drops from 35 km.
[18]	FSO-DWDM environment with different advanced modulation format (AMI, Duobinary, Chirped NRZ and 33% RZ).	All the four proposed models can support the transmission rate up to 10 Gb/s. The result shows that AMI, Duo binary and CNRZ can support up to 7 km and 33% RZ can support up to 6 km range of FSO.
[19]	Eleven-channel DWDM over FSO based on the electrical linear equalizer with 1.2 nm spectral width.	10 Gb/s data has been transmitted over eleven-channel under the effect of clear air, haze and rain atmospheric attenuations based on electrical linear equalizer that reached the distances 9500 meters, 300 meters and 2500 meters, respectively.
This paper	DWDM-FSO based on OFDM modulation technique with 0.8 nm spectral width.	Achieved up to 4x21 Gb/s with maximum 100 km of FSO link at BER of $10e^{-9}$ and Q-factor of 27.26.

4. Conclusions

In conclusion, this study successfully demonstrated a 15 Gb/s DWDM over FSO communication system using the OFDM technique, achieving effective transmission over distances ranging from 50 km to 100 km downstream. OFDM modulation was used to investigate the performance of the proposed design of DWDM over FSO with various parameters such as signal power, FSO transmitter and receiver diameter, attenuation, and distance. The system was designed with four channels of 10 GHz each with 15 Gb/s to evaluate the performance of the OFDM technique as well as to analyse the better results at BER and Q-factor based on the data rate, neither of which are suitable for the environment. Furthermore, a single OFDM system was investigated, and it was discovered that an OFDM DWDM system is more reliable for high data rates. It is concluded that OFDM provides excellent performance in DWDM over FSO communication systems; additionally, the FSO receiver and transmitter diameter range increases as transmitter power increases. In future, the potential of this OFDM technique or system will be used even in adverse weather conditions and that it will be able to be used over long distances to generate or provide better performance to the environment and humidity. All in all, the future of DWDM-FSO based on OFDM appears bright, as demand for high-speed data transfer and dependable connectivity grows. However, more research and development are required to address the technical challenges associated with this technology, as well as to ensure its practicability and scalability for commercial use.

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